An Approach to Estimating Surface Parameters and Fluxes using Modeling and Multispectral Remote Sensing

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ABSTRACT

Water rrnd energy exchanges at the land-atmosphere interface play a kc y role in determining patterns of regional and global climate. However, accurate estimation of surface fluxes of sensible and latent over arid and semiarid regions is a challenging task. In this study, a scenario for assimilating satellite data in the visible-infrared (AVHRR) and in the microwave (SSM/I) spectral ranges in a hydrological flux model will be presented. The aim of our investigation over the HAPEX-Sahel area in West Africa is to show that the *use* of multispectral remotely sensed data, in conjunction with radiative transfer models and a hydrological flux model, can provide reasonable estimates of the surface fluxes. A discussion of the potentials rrnd limitations of the approach is presented.

1 INTRODUCTION

Spaceborne remote sensing provides a means for repetitive sampling of the Earth's surface and atmosphere over large areas, over long time periods, and at a variety of spatial and temporal resolutions. Such measurements are useful and perhaps essential for improving models of geophysical and climate processes and for studies of global change. Yet progress in the use of remote sensing data in land hydrometeorological studies has been slow. Many problems remain in demonstrating the accuracy of remotely sensed measurements and in defining methods for coupling remote sensing data with hydrologic and energy flux models (data assimilation). Two particular difficulties in the assimilation problem are: (1) defining an appropriate. parameterization for the coupling of remote sensing and land biophysical models so that the remotely sensed data provide information that can be used directly in the models; and (2) accounting for the differences in spatial and temporal resolutions at which the remote sensing measurements are made and at which the geophysical models operate. This is particularly important for regions wirh heterogeneous mixtures of surface types and resulting surface fluxes such as encountered *in* semiarid environments.

In this paper a scenario is developed for combining remotely sensed measurements of land surface parameters with a simple biophysical flux model in order to study the nature of the problems listed above and to develop possible approaches to overcoming them. The scenario is formulated for application to the environment and conditions of the HAPEX-Sahel experiment in order to investigate the possibility of deriving surface fluxes and soil moisture over the HAPEX-Sahel study site using available visible-infrared (AVHRR) and passive microwave (SSM/I) satellite data. In the first step a biophysical model is developed whose parameters can be directly related to the remote sensing observations. in the second step a retrieval scheme is developed in which the flux components of the energy balance equation and the vegetation and soil moisture are estimated using the remote sensing measurements. This retrieval scheme may be used to study the sensitivity of the method to specific measurement and model uncertainties, and to test the applicability of the method in a given environment using the HAPEX-Sahel experiment data.

FLUX MODEL PARAMETERIZATION

A basic one-layer model is used to describe the exchange of energy between the surface and the atmosphere. The energy balance equation is expressed as:

$$R_n = LE + H + G \tag{1}$$

where R_n is the net radiation and G, H, and LE are the soil, sensible, and latent beat fluxes, respectively. These terms are expressed as:

$$H = \rho\, C_p (T_s - T_a) / r_a \tag{2}$$

$$LE = \rho \left(C_p/\gamma\right)\left(e^*(T_s) - e_a\right) / (r_a + r_s) \tag{3}$$

$$R_n = (1 - \alpha) R_s + \varepsilon \left(R_l - \sigma T_s^4\right) \tag{4}$$

where p is the mean air density, C_p is the specific beat of air at constant pressure, γ is the psychometric constant, T_a and e_a are the air temperature and vapor pressure at a reference height, and $e^*(T_s)$ is the saturated vapor pressure at surface temperature T_s. R_s and R_l are the incoming short- and long-wave radiation, respectively, and ε is the surface emissivity. T_s can be derived from the thermal infrared channels (channels 4 and 5) of the Advanced Very High Resolution Radiometer (AVHRR) following the procedure of Kerr et al. (1992). The surface albedo, α, may be derived from AVHRR channels 1 and 2 in conjunction with a bidirectional model used to infer hemispherical reflectances independent of viewing angle (Cabot and Dedieu, 1994). These hemispherical reflectance are also used to compute a Modified Soil-Adjusted Vegetarian Index ($MSAVI$) (Qi et al., 1994a, 1994 b). The soil heat flux, G, represents a significant component of the energy balance in sparsely vegetated surfaces and can be expressed as a function of the net radiation and the $MSAVI$ as follows (Jackson et al., 1987):

$$G = R_n [\, 0.S5 \exp(-2.13\, MSAVI)] \tag{5}$$

The aerodynamic resistance, r_a, is corrected for stability using the Mahrt and Ek (1984) formulation. The surface resistance to water transfer, r_s, *is* expressed as the product of a minimum surface resistance, r_{smin}, a solar radiation factor, F_1, which decreases surface resistance from a large value at night to a minimum value near noon (stomatal control), and a water stress factor, F_2:

$$r_s = (F_1\, r_{smin}) / (F_2\, LAI) \tag{6}$$

$$F_1 = (1 + 0.01\ R_s)/\ (0.01\ R_s + r_{smin}/r_{smax}) \qquad (7)$$

$$F_2 = 1 - \{(\theta_r - \theta_s)/(\theta_{fc} - \theta_w)\} \qquad (8)$$

These expressions are. comparable in form to those used by Pinty et al. (1989) and Noilhan and Planton (1989). In these expressions *LAI is* the leaf area index (which can be computed from *MSAVI*), r_{smax} is the maximum surface resistance, θ_r is the soil moisture in the root zone, and θ_s is the surface soil moisture. θ_w and θ_{fc} are the soil moisture at wilting point and field capacity, respectively; both are functions of the soil type. Equation (8) is expected to be a useful representation for interstorm periods in semiarid environments.

OBSERVATIONS

Using surface meteorological measurements and AVHRR-derived surface temperature and albedo, the latent heat flux *LE* can be computed as a residual of the energy balance equation by combining equations (1), (2), (4), and (5). *LE* may also be computed directly using equations (3), (6), (7), and (8). By equating these two results, a nonlinear functional constraint is obtained on the two variables θ_r and θ_s contributing to the water stress factor F_2, i.e.:

$$\theta_r = F\ (\theta_s) \qquad (9)$$

The surface soil moisture θ_s is amenable to microwave remote sensing as is the vegetation water content w_v (Kerr and Njoku, I W()). However, the moisture in the root zone cannot be measured directly. For a bare soil, the deeper-layer moisture can be inferred from surface remotely sensed measurements with a soil flux model as described by Entekhabi et al. (1994). For a vegetated surface, a Relationship may be established between the root zone moisture and the vegetation water potential. It may further be possible to establish a link between the vegetation water potential and vegetation water content under certain specific and well-calibrated conditions. Recent data from the HA1'IIX-Sahel experiment sites (N. Hanan, personal communication) indicate that, for these specific sites and conditions, a linear relationship exists between vegetation water content and soil moisture in the root zone, of the form:

$$w_v = a\ \theta_r + b \qquad (10)$$

where a and b are empirical parameters that depend on the vegetation type.

Equations (9) and (10) potentially provide a means for using multispectral passive microwave and visible-infrared data in combination to check the self-consistency of the surface flux parameterizations and the remote sensing observations. If low frequency passive microwave measurements are available (e.g. !,- and C-band measurements at -1.4 and 5 GHz), then in regions of low to moderate vegetation it is possible to estimate both θ_s and w,. The system of equations is then over-determined and the self-consistency of the models and measurements may be tested. If higher frequency microwave measurements only are available (e.g. higher than C-band), such that the vegetation is 100 opaque to permit estimation of surface soil moisture but still permits estimation of vegetation moisture, then the system is evenly-determined and microwave measurements of w, allow estimates of θ_s to be made by solving equations (9) and (10). In this paper a scenario for the latter case is discussed since wc wish to address the potential use of spaceborne data; the only passive microwave surface imaging system currently in orbit is the Special Sensor Microwave image.r (SSM/I) which has frequencies in the relatively high range of 19.35 to 85.5 GHz.

RETRIEVAL SCHEME

The key features of the retrieval scheme. in this scenario are the use of data from the AVHRR to estimate T_s, α, and *MSAVI*, and of data from the SSM/I to estimate w_v. The remaining parameters in the model equations are obtained from available surface meteorological measurements (referred to here as MET data) or from a-priori estimates of the soil and vegetation characteristics. An immediate problem in implementing this scenario is that the AVHRR, SSM/I, and MET measurements are made at different times of day and represent different spatial scales. Since the SSM/I data are the coarsest in space and time resolution of the data used in this study, the final retrievals of fluxes and vegetation and soil moisture are done at the SSM/I resolution. The steps in the procedure are as follows:

(1) 1-km resolution AVHRR data from NOAA-11 and NOAA-12 are resampled to a 102x102 pixel image array (rectangular latitude-longitude grid) bounded by the HAPEX-Sahel study region 2" to 3°E and 13" to 14-N.

(2) Surface temperature T_s, and albedo α, arc computed for each AVHRR image. A bidirectional function for albedo, and an empirical relation for temperature arc used to translate these values to the time of the SSM/I overpass.

(3) Tbc T_s, α, and hemispherical reflectance values are averaged onto a 2x2 an ay ($\frac{1}{2}^\circ$ x $\frac{1}{2}^\circ$ pixels) within the HAPEX study region. The SSMI data are interpolated to this same grid. The MET data are interpolated in space and time to the same grid and *MSAVI is* computed from the hemispherical reflectance. The size of this grid (approximately 50 km) corresponds to the approximate SSM/I footprint size at 19.35 GHz.

(4) The surface flux model is run at the 2x2. array grid scale using the AVHRR-derived surface parameters and the MET data to determine H, R_n, G, and LE (as a residual of the energy balance equation).

(5) 'The AVHRR-derived surface parameters and the SSM/I brightness temperatures at 19,35 and 37 GHz are used to solve for w_v, and, through the constraint of equation (9) a value for θ_s is also obtained. This procedure is done by iteration.

The outputs of the above steps are values for the surface fluxes (H, R_n, G, LE) and surface parameters (T_s, a, *MSAVI*, w_v, θ_s) at the 2x2 array grid scale.

DISCUSSION

In the initial testing of this procedure, available data from the HAPEX Sahel experiment during the month of September 1992 were used, Four SSM/I channels (19.35 and 37 GHz, vertical and horizontal) were included in the estimation of vegetation water content using a simplified radiative transfer model as the basis for the retrieval. It was found that the retrieval gave better results if the vertically polarized channels only were used, indicating possible deficiencies in the radiative transfer model at horizontal polarization. Some anomalies were also observed in the AVHRR surface temperature retrievals. Nevertheless, in most cases the resulting fluxes and surface parameters gave reasonable values. A more detailed analysis and comparison with other HAPEX Sahel data is currently in progress.

The initial formulation of this approach has been greatly simplified relative to actual surface conditions in order to implement the first step of coupling the remote sensing and energy flux models. In analyzing results from and improving upon this formulation the following points are being considered:

(1) How accurate are the formulations for energy fluxes in terms of surface resistances over heterogeneous terrain?

(2) How accurate are the parameters estimated from the remote sensing data (T_s, α, $MSAVI$, w_v) over heterogeneous terrain?

(3) How do errors in estimating the components of the energy balance equation propagate into errors in the estimation of vegetation water content and soil moisture?

(4) What are the additional sources of errors that must be accounted for (e.g. those resulting from space-time interpolation and averaging to lower resolut ions) before such an approach can be applied operationally?

Continuing research into these issues will enable better assessment of the future potential of multispectral spaceborne remote sensing in monitoring the space-lime variations of surface fluxes anti in estimating the water status of soii and vegetation in semiarid regions.

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